NASA TECHNICAL NOTE

NASA TN D-4055

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NASA TN D-4055

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JULY 1967

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SUMMARY

Nine mercury electron-bombardment thrustors were operated for periods up to 4870 hours. Eight of these thrustors produced a 15-centimeter-diameter beam and were operated with 0.25-ampere beam current; the other thrustor produced a 20-centimeter-diameter beam and was operated with 0.40-ampere beam current. A net acceleration potential of 3000 volts was used. The thrustors were tested in two vacuum facilities, one of which was 1.5 meters in diameter by 5 meters long and the other, 7.5 meters in diameter by 21 meters long.

Various cathode types were tested in this program. One type was an oxide-coated cathode with various methods of oxide-matrix support and emitter surface heating. Another type was an oxide-magazine cathode that utilized a hot-tungsten screen with a supply of oxide pressed against the surface. This type, considered the most promising, had a demonstrated lifetime of 4179 hours. A cathode changer was also evaluated.

INTRODUCTION

Cathodes suitable for long-life electron-bombardment ion thrustors have been tested extensively (refs. 1 to 3). One promising oxide-cathode concept tested has exhibited lifetimes up to 5019 hours during simulated thrustor operation (ref. 1), that is, with no extraction of a beam from the discharge chamber. The cathode environment in operating thrustors, however, usually proved to be more severe because of the occasional arcing in the ion chamber as a result of high-voltage breakdown between the accelerator grids. The tests presented herein evaluated several oxide-cathode concepts to determine their lifetimes in an operating ion thrustor. A goal of these tests was to obtain a cathode with a demonstrated lifetime of at least 3000 hours and a design lifetime of 10 000 hours. Earlier cathode tests conducted in operating ion thrustors and preliminary tests performed in the present study are described in reference 4.

As longer lifetimes were obtained from the oxide cathode, it became apparent that cathode sputtering was the prime mechanism that led to a deterioration of thrustor performance. Increasing the thickness of the oxide layer produced the greatest gains. This thickness, however, could not be increased indefinitely. This report describes in detail a new cathode concept, the oxide-magazine cathode, which provides in a simple manner, a continuous supply of oxide to the cathode.

Eight 15-centimeter-diameter and one 20-centimeter-diameter ion thrustors were used in the present tests, which were conducted in two vacuum facilities. The cathodes were operated continuously for periods up to 4870 hours. The results of measurements of the accelerator grid erosion that occurred during these tests is presented in reference 5.

APPARATUS

Thrustor

Cutaway drawings of the two sizes of thrustor used are presented in figures 1 and 2. Extensive data on the performance of the mercury electron-bombardment thrustor are presented in references 6 to 8.

Briefly, the operation of the thrustor is as follows: Liquid mercury is supplied under pressure (greater than the vapor pressure) to the vaporizer. The vaporizer consists of a 6-millimeter-outside-diameter molybdenum tube with a swaged wire heater brazed around the downstream end. A porous tungsten plug, which serves both as a phase separator when heated and as a valve when cold, is located in the tube beneath the heater element. (The cold plug can withstand 2 atm of liquid mercury pressure without leakage.) The mercury vapor flows into a manifold (annular for the 15-cm thrustor and an extension of the thrustor body for the 20-cm size) and then into the ion chamber. The ion chamber contains the cathode and a cylindrical anode. Electrons emitted from the cathode on the axis of the chamber bombard the atoms of propellant vapor and thereby ionize some of them.

The discharge is contained by a nearly axial magnetic field (stronger at the upstream end). Most of the ions that diffuse to the downstream end of the chamber are focused and accelerated into the exhaust beam by the potentials applied to the screen and accelerator grids. This exhaust ion beam can be neutralized by electrons emitted from either of two neutralizers located at the periphery of the beam.

The screen and accelerator grids are drilled molybdenum. The thickness, hole size, and typical spacing of the two grids for both thrustors are shown in figure 1. The remainder of the thrustor, with the exception of the magnetic-field windings, the cathode, and the insulators, was fabricated of nonmagnetic stainless steel. The 15-centimeter thrustor design allowed the cathode to be removed easily from the unit without the necessity of dismantling the thrustor or its associated electrical wiring. Small differences in thrustor construction existed because of the use of modified cathodes, cathode changers, and permanent magnets. The physical characteristics of the cathodes used are given in table I. Additional descriptions of particular cathodes are provided as the results are discussed.

Electrical System

A schematic diagram of the electrical system used to life-test the mercury bombardment thrustors is shown in figure 3. Of the four control loops that were used for the tests (fig. 3), two were used to maintain both the anode and accelerator voltages constant under varying loads and to recycle these units in the event of a high-voltage arc. A third control loop was incorporated to monitor the accelerator and the grid impingement current and to adjust the vaporizer power (flow rate) accordingly. The fourth control loop monitored and adjusted the cathode emission current by utilizing the discharge voltage as a control. The control system and its various loops are more fully described in reference 4.

Facilities

Two vacuum facilities were used to conduct these tests. The 15-centimeter-diameter thrustor was installed in a vacuum tank 1.5 meters in diameter by 5 meters long (fig. 4). Thrustor operation was possible at pressures of approximately 2×10^{-6} millimeter of mercury (27×10^{-4} N/m^2).

Figure 5 shows the eight thrustor stations in the 21-meter-long vacuum facility. Thrustors 1 to 4 and 6 to 9 were located in the 7.5- by 21-meter facility, and thrustor 5 was located in the smaller vacuum tank. Only four of the eight thrustors tested in the larger facility were operated at one time, since only four thrustor electrical systems were available. The four thrustors (6 to 9) in the 3-meter-diameter by 3-meter-long test compartment could be isolated from the main tank by a 3-meter-diameter gate valve. The facility maintains a pressure of approximately 1×10^{-7} millimeter of mercury (1.3×10^{-5} N/m^2) with the four thrustors in operation. The larger vacuum tank is described in considerable detail in reference 9.

Each of the two vacuum facilities utilized a honeycomb target to reduce backsputtering. The honeycomb, constructed from 0.075-millimeter-thick aluminum, was

3.8 centimeters deep with a length-diameter ratio of 10 for the holes. Each of the four thrustors in the larger facility was aimed at the center of the target.

PROCEDURE

Cathode endurance tests in operating thrustors were run at constant ion beam current, anode voltage, and accelerator voltage. The heating power to the cathode was varied to maintain the ion beam current constant. The discharge voltage (anode to cathode voltage), which also affected the cathode emission current, was kept as low as possible, since the rate of sputtering of the cathode is a strong function of the impinging ion energy. It was, however, necessary to vary the discharge voltage over a range of values in each test, since cathode performance deteriorated, and increasing power was required for constant cathode emission. Small increases in the discharge voltage were therefore permitted during the tests. However, a time plot of the cathode heating power necessary to maintain the beam level was the most reliable data to determine cathode condition. Small variations in magnetic-field strength were also permitted. The ion beam current and net accelerative voltage were maintained at values believed suitable for thrustor operation under flight conditions.

The range of values of the operating parameters is presented in table II. The length of the various cathode tests is included in table I. In some cases (thrustors 8 and 9), grid shorting prevented ion beam extraction. These thrustors were then operated, for the remainder of the respective tests, as simulated thrustors with constant cathode emission current being maintained.

RESULTS AND DISCUSSION

Previous cathode tests (ref. 4) indicated that factors existed which limited the oxide-coated lifetime. The cathode emission was apparently coming from hot spots on the cathode and not uniformly from the entire surface. In addition, the radial thermal gradient within the cathode was large and thereby increased chemical corrosion rates in the cathode interior (consumed the tantalum support structure in some cases). Some initial tests that explored these problem areas are presented in references 1 and 4. The results for the brush cathode indicated that smaller diameter cathodes with thicker or a a greater number of tungsten bristles are desirable to reduce the radial thermal gradient. The tungsten bristle also offers the advantage of relative immunity from chemical attack, but it requires the addition of a chemical activator. These considerations were made to extend the lifetime of the brush cathodes tested in this investigation. In addition to the brush-type cathode, two other methods for eliminating cathode lifetime limitations were employed. The three approaches to the cathode problem are reported in the following order: (1) brush-type cathodes, (2) indirectly heated cathodes, and (3) oxide-magazine cathodes.

Brush-Type Cathode

Single cathode. - The construction of brush cathodes was similar to that used in reference 10. Thin wires were attached to a heavier center wire in the manner of a radial wire brush. The thin wires provided a support for the oxide coating while the heating current was supplied through the center wires. The oxide was hydraulically pressed into the bristles after they were coated. Brush-type cathodes were operated in thrustors 1, 2, 4, 7, and 8. The cathodes in thrustor 8 were mounted on a cathode changer. The bristles used in the cathode were tungsten in all brushes except thrustor 2, which had a ratio of tungsten to tantalum bristles of 3. This cathode was the only brush cathode that did not have carbon activator added to the barium carbonate, because the quantity of tantalum bristles was probably sufficient to provide the necessary activation. The use of both carbon and tantalum as chemical activators is described in reference 1.

Barium carbonate was used as the oxide coating on all the brush cathodes used. The brush core wires were either tungsten or tantalum. Ease of construction and a higher electrical resistivity made tantalum more desirable, since a more tightly wound brush that required less heating current could be obtained. A brush cathode before its use in the thrustor is shown in figure 6.

The cathode heating power as a function of time is presented in figure 7 for all brush cathodes except those used in the cathode changer. (The heating power for the brush cathodes used in the cathode changer is presented separately.) A general deterioration of all brush cathode emitting surfaces was evidenced by an increased power level with time. This deterioration is believed to be caused by several factors: deposition of sputtered material from the ion chamber onto the cathode surface, erosion of the emitting surfaces by ion bombardment, and depletion of the activator.

The 8.9-centimeter-long brush cathode of thrustor 1 had an emission current of about 0.2 ampere per square centimeter and a nominal heating power of 7.1 watts per square centimeter, which was the lowest of all cathodes tested. The cathode power rose rapidly during the first 200 hours and then increased at the constant rate of about 20 watts per thousand hours until the cathode was turned off after 4870 hours of operation because of an electrical short circuit that developed across the grid high-voltage insulators. Inspection of the cathode after testing indicated that the major portion of the oxide was still present and that a dark coating existed over the surface of the cathode. No deterioration of the bristles was observed. These observations were true for all brush-type cathodes tested in this program.

The cathode in thrustor 2 operated at a cathode power level about 30 watts higher than that of thrustor 1. The rate of power increase was about the same as that of thrustor 1. The cathode heater opened up after 1809 hours of operation. An inspection of the fracture in the heating wires indicated that neither chemical attack nor excessive heat was responsible for the failure. A localized strain and defect in a tantalum heating wire could have caused this failure.

The cathode in thrustor 4 was operated at a higher power level than those of thrustors 1 and 2. The cathode power level was about 15 percent greater than that of cathode 1, even though both cathodes utilized the same percentage mixture of barium carbonate and carbon. Although differences existed in the number and size of tungsten bristles, the major difference was felt to be the smaller diameter of the number 1 cathode, which permitted a smaller radial temperature gradient within the cathode.

The cathode in thrustor 7 operated at increasing power levels until the run was terminated at 1150 hours because of the high cathode power. This cathode was the same as cathode 4 except for the greater amount of carbon activator present. As can be seen from the nominal cathode power in table II, the cathodes with greater amounts of activator operated at about twice the power per square centimeter as the cathodes with the stoichiometric mixture of activator. (The stoichiometric quantity was defined as one atom of carbon for every atom of barium, or 5.7 percent by weight of carbon mixed with barium carbonate.)

Cathode changer. - Longer-term testing of a cathode changer was undertaken to determine the practicality of replacing eroded or damaged oxide cathodes after sustained thrustor operation. Preliminary short-term tests described in reference 5 demonstrated the feasibility of this concept. The cathode changer (fig. 3) contained four oxide cathodes that were mounted in a drum that could be rotated into the ion chamber by turning a shaft. A cathode in operating position, as installed in the thrustor, is shown in figure 8(a). The axis of the cathode was normal to the axis of the thrustor. Heater shields were added to the cathode drum to reduce the radiated heat losses. The replacement cathodes are shown in figure 8(b), along with one of the electrical contacts and the drive shaft. Electrical contact is made through stationary cylindrical carbon brushes and copper contacts at each cathode position. The cathode changer was installed on thrustor 8 and operated for 158 hours, after which a short circuit in the grid system occurred. The cathode was then operated in the source with no accelerating voltage present for the remainder of the test.

The first cathode in the changer was operated for a total of 1361 hours, after which the second cathode was rotated into operating position. A torque measurement indicated that 3 newton-meters were necessary to start the drum rotating and that 2 newton-meters were necessary to maintain the movement. These torque levels were felt to be reasonable on the basis of the bearings, the gear train, the vacuum seal, and the universal joint in the system. The second cathode was then operated for 1441 hours, after which the third cathode was rotated into place with about the same torque being necessary. The cathode power as a function of time is presented for the first two cathodes in figure 9. No long-term deterioration of the changer mechanism was noted upon inspection at the end of the tests.

Some disadvantages of the cathode changer were noted during thrustor operation, however. The cathode power level was excessively high (200 to 350 W) for the size of the emitting area (12.8 sq cm) tested. Some of the power to the cathodes, however, was probably dissipated in the electric contacts. Careful contact design should eliminate this problem. A second disadvantage was the relatively poor thrustor performance obtained while this cathode was used (table II). Thrustor performance might improve if the cathode placement were varied.

Indirectly Heated Cathodes

Two of the cathodes used in the cathode durability tests employed indirectly heated elements. The purpose of this design was to protect the cathode heating element by enclosing it in a tantalum tube. Ceramic inside the tube aided in the transfer of heat from the heating element, and the emissive oxide coating was placed on the outside of the tantalum tube. The tube also provided a uniformly heated surface that would minimize localized hot spots on the cathode. The construction of the heating elements was essentially the same for both cathodes. The heater was coiled around a threaded spool, and the assembly was inserted into an insulated tube, which was in turn inserted into a tantalum tube. The entire assembly was then swaged. The oxide coating, which was different for each of the two cathodes used, was attached to a 0.45-centimeter-outside-diameter tantalum tube support structure. A 5-millimeter-diameter tantalum brush was wrapped around the tantalum tube of the cathode of thrustor 3. The oxide was then added to the brush, and the cathode was hydrostatically pressed at a pressure of 34×10^{7} newtons per square meter. For thrustor 9, corrugated iridium washers were attached to the tantalum tube of the cathode, oxide was then packed between the washer spacings. The cathode of thrustor 9 is shown in figure 10. The cathode of thrustor 9 was longer and had a larger diameter than that of thrustor 3, since a greater emission current was necessary in the larger (20 cm diam) thrustor. Radio Mix Number 3 (57 percent barium carbonate ($BaCO_3$), 42 percent strontium carbonate ($SrCO_3$), and 1 percent calcium carbonate ($CaCO_3$)) was used in both indirectly heated cathodes.

The cathode power as a function of time is presented in figure 11 for both indirectly heated cathodes. The cathode power to thrustor 9 rapidly increased at a rate of about 300 watts per thousand hours. The accelerator grids shorted at 158 hours, but cathode operation was continued in the ion chamber without beam extraction for a period of 1360 hours. The test was stopped after 1360 hours because of the high cathode power level. The poor performance of this cathode was apparently the result of the lack of activator in the triple carbonate. Inspection of the cathode after the test indicated that about one-half of the oxide coating remained. No deterioration of the iridium washers was noted.

The cathode in thrustor 3 had a relatively stable power level for the first 1000 hours, after which a steady increase in power was observed. The cathode heater failed after 2060 hours of operation. Examination of the cathode indicated that the oxide had been depleted almost completely. An estimated 5 percent or less of the oxide remained on the cathode. The supporting tantalum brush was also consumed.

In general, the results obtained with the indirectly heated cathode paralleled those obtained with the brush-type cathode. Surface deterioration still occurred, which resulted in an attendant rise in cathode power until the heating element failed. An improved design of the oxide-coated structure for the indirectly heated cathode containing the proper amounts of activator should provide comparable lifetimes with those obtained with the brush-type cathode. The heating element for such a design should also be more reliable than that of the brush-type cathode design because the chemical attack on the heating element should be reduced.

Oxide-Magazine Cathode

Successful oxide-coated cathodes have been operated in a variety of configurations in the mercury electron-bombardment ion thrustor. The active emitting surface of the oxide cathode is continually bombarded by ions from the discharge, which cause sputtering erosion and damage of this active surface. The typical solution to this problem in the cathodes described previously is to provide either an increased supply of oxide, or more surface area, or both.

An increased thickness of the oxide layer, however, causes thermal and electrical conduction problems. Very careful design is required to avoid hot-spot emission and the resultant destruction of the oxide surface. The thermal conduction problems lead to a long emission response time with respect to the cathode heater and can result in thrustor control problems. Increased surface area requires ingenuity in arranging the surfaces to give both acceptable ion-chamber performance and a reasonable heating power requirement.

The oxide-magazine cathode was designed to incorporate a large quantity of active material while minimizing the coverage of the heater element. A cutaway sketch of the oxide magazine cathode is presented in figure 12. The cathode is composed of a directly heated tungsten screen that acts as a substrate for the active emitting material, a duct that contains blocks of a mixture of barium carbonate and carbon, and a spring-loaded piston that forces the blocks down the duct into contact with the tungsten screen.

The tungsten screen was woven from 0.13-millimeter- (5 mil) and 0.09-millimeter- (3.7 mil) diameter wire with a 10- by 120-per-centimeter mesh, respectively. The screen was so designed that the heater current passed through the screen in the 10-mesh direction and thus minimized the required heating current. The screen was mounted on a boron nitride or aluminum oxide insulator by shaping the screen and holding it at the ends. The ends of the screen were clamped between copper contact blocks. The duct and piston were fabricated of stainless steel and the spring of tungsten wire.

Initial tests. - The conceptual design consisted of the screen heater element with barium carbonate powder pushed down a tube by a spring-loaded piston. Tests showed that loose powder jammed the tightly fitting piston. This problem was eliminated by using granules of carbonate larger than the piston clearance. Producing the granules required hydrostatically pressing the carbonate and then crushing the blocks, which resulted in the proper grain size. The first tests that used granulated carbonate were conducted in a configuration shown in figure 13(a). Only a few milliamperes of emission were obtained with this configuration until carbon was added to the granules to act as an activator. Several hundred milliamperes of emission were obtained before an emission limit was reached. After the cathode was operated for 15 to 20 minutes, the emission ceased. Later inspection showed a depletion of the activator in the vicinity of the screen. The proportion of carbon was increased from 5.7 percent to 8.5 percent (by weight). The pressed blocks were not granulated but were cut to shape and put into the cathode, as shown in figure 13(b). The screen area was increased through the addition of angular blocks (shown on the figure). This configuration produced several amperes of emission during an overnight test, although at a somewhat higher temperature (about 150° C) than desired. These tests resulted in the design for the final configuration (fig. 12), which normally operated at a temperature near 950° C as determined by an optical pyrometer. This cathode has a greater emitter area and a mount configuration that reduces thermal conduction leakages.

Cathode performance. - Typical power-emission characteristics of the final oxide cathode exhibited an increasing emission with increasing power near the normal operating region (4 A emission at a 0.25 A-beam current). Higher emissions than those shown in figure 14 were not attempted during the endurance test. This rise in emission possibly indicates that a certain temperature is necessary to promote the barium oxide - carbon reaction and to cause barium to be dispensed to the surface of the screen. The dashed line indicates the hysteresis that exists as the power is reduced. This hysteresis could be due to excess active material that accumulates on the cathode surface at the higher power levels. The emission dropped with time (about 1 hr) to a value just above the original power-emission curve.

The cathode emission also responds to ion-chamber potential difference, as shown in figure 15. The emission current increases with increasing discharge voltage until a maximum is reached. Further increases in the discharge voltage result in a lowering of emission current. These curves are repeatable, starting at any point on the curve and waiting about 30 minutes between data points for the cathode emission to stabilize. The decreasing emission current at higher discharge voltages is assumed to be caused by an excessive rate of removal of cathode emission to stabilize. The decreasing emission current at higher discharge voltages is assumed to be caused by an excessive rate of removal of cathode surface material as a result of the higher energy of the bombarding discharge ions. The trend of an increasing emission current at a lower discharge voltage could be caused by the following: (1) increased activation of the surface resulting from moderate ion bombardment, (2) a space-charge limited condition at the surface of the cathode, or (3) ion bombardment heating of the surface, increasing with discharge voltage. The sputtering yield of mercury ions in the range of 25 to 50 volts increases exponentially. While some ion bombardment may be beneficial, an excess can cause a serious loss of emission and, undoubtably, lifetime. An upper limit of 35 volts for the discharge voltage seems strongly indicated by the data, and longer lifetimes will probably result if the discharge voltage is held below 30 volts. The oxide-magazine cathode of thrustor 6 was operated at a discharge of 25 volts.

The discharge chamber plasma is usually extinguished in the range from 20 to 25 volts because of the decreasing ionization cross section of the mercury propellant. The particular voltage at which the discharge ceases is determined by the propellant density, the location of the cathode, and the shape and the strength of the magnetic field.

The magnetic-field strength in the ion chamber influences the emission characteristics of the cathode; however, within the range of field strengths used for optimized ion-chamber performance, the effect is minor. In general, higher field strengths slightly increase the emission.

Thrustor tests were performed with an oxide-magazine cathode to determine the steady-state control properties, as in reference 7. The nondimensional curves of the beam-current ratio to the cathode-emission current ratio matched those of reference 7 exactly.

Durability tests. - Two long-duration tests were performed utilizing oxide-magazine cathodes the same as the one shown in figure 12. One cathode (thrustor 5) was installed in the smaller vacuum facility and operated for 4179 hours. The other cathode (thrustor 6) was installed in the larger vacuum facility and operated for 3240 hours. The cathodes were operated at slightly different values of discharge voltage.

Both tests were terminated voluntarily to inspect the cathodes.

Figure 16 is a plot of cathode power against operating time for these two tests. These power values were calculated from panel-meter readings and do not compensate for losses due to electrical leads inside the vacuum facility. The cathode of thrustor 6 in the larger facility (long leads) operated consistently at about 50 watts above the cathode of thrustor 5 in the smaller facility. The heating current to both cathodes, plotted in figure 17, was about the same and indicated that the heating power difference was probably due to the lead losses. The power level to the cathode of thrustor 6 would normally be expected to be somewhat below that of the cathode of thrustor 5 because of the slightly higher discharge voltage used.

After an initial conditioning period, the power to both cathodes remained approximately constant for the first 1000 hours of operation and then began to increase slowly. The increase was fairly linear at about 20 watts per 1000 hours, which corresponds to the rate most commonly observed with the brush-type cathodes. This linearity is felt, however, to be coincidental.

An enlarged view of the discharge chamber side of the cathode heater-emitter screen after 3240 hours of operation (thrustor 6) is shown in figure 18. Figure 18(a) is a photograph of a new piece of screen. The wires suffered little, if any, erosion during operation. The wire diameter was the same as that of a new screen. The flakes and dots visible on the surface were collected and spectrographically analyzed. They consisted of condensed sputtered material (iron and molybdenum) mainly from the thrustor ion chamber. Tungsten was a prominent element and was felt to be present mainly as a result of the sample collection process. Some elements (copper and aluminum) from the vacuum tank walls were also identified. The cathode heater-emitter screen of thrustor 5 after 4179 hours of operation was similar to that of thrustor 6. The condensed sputtered material, however, was not felt to constitute a problem to cathode operation.

There was no indication in either cathode that the piston advanced during the duration tests of thrustors 5 and 6. The end of the cathode of thrustor 5 with the screen swung out of the way to expose the oxide block is shown in figure 19. The surface of the block was about 0.3 centimeter away from the heater-emitter screen and was tightly held in place both in the metal duct and in the boron nitride insulator. The cathode of thrustor 6 was the same. Figure 20 shows the oxide blocks removed from the cathode. The block from the metal duct appeared to be in about the same condition as when it was installed originally. The white color evident on the screen side of the block from near the cathode emitting surface indicated that the carbon activator had been depleted. A cutaway of the first emitting block from thrustor 5 revealing the depth of carbon depletion is presented in figure 21.

Two possible reasons existed for the observed cathode power increase with time. The major reason probably was that the increasing distance between the oxide block and the heater surface resulted in poorer heat transfer from the heater to the oxide block. A second possible reason was that an unbalance in activator depletion within the block resulted in less barium production and less cathode activation.

The resistance characteristics of the two cathodes did not change with time, which supports the visual observation that no tungsten screen erosion existed; hence, erosion of the screen should be no problem for a 10 000 hour lifetime. The rate of supplying active material to the screen was thought to diminish with operating time primarily because of the seizing of the oxide blocks. The reason for the block seizing was an expansion in size during thrustor operation. This expansion may be caused by the evaporation of water vapor and stearic acid (a binder used in hydrostatic pressing) during heating. Subsequent tests made on a block showed an increase in size when it was heated. This expansion could be eliminated or reduced by any of several methods, one of which is preheating the block before operation and then shaping it to fit within the magazine. With the blocks free to move, the rate of cathode power increase should be considerably reduced or eliminated.

SUMMARY OF RESULTS

The following cathode results were obtained from the endurance tests of nine mercury electron-bombardment ion thrustors:

1. Brush-type cathodes had demonstrated lifetimes of up to 4870 hours. Cathode power increased with time (20 W/1000 hr), which imposed a lifetime limitation on the brush-type cathodes.

2. A cathode changer was demonstrated to be practical. A changer utilizing four cathodes operated in an ion source for over 1000 hours on each of two cathodes. No major mechanical problems were encountered.

3. Indirectly heated cathodes had demonstrated lifetimes of up to 2060 hours, but cathode power increases placed a limit on lifetime.

4. Oxide-magazine cathodes had demonstrated lifetimes of up to 4179 hours. Cathode power increased with time (20 W/1000 hr) after about 1000 hours of stable operation. The reason for the cathode power increase is presently attributed to binding of the oxide block within its duct passage. Elimination of this problem should provide a low-power cathode with lifetimes greater than 10 000 hours.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 5, 1967,
120-26-02-05-22.

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TABLE I. - CATHODES USED IN ENDURANCE TESTING AND TEST DURATIONS

Thrustor	Core wire		Bristle wire		Cathode diameter, cm		Cathode length, cm		Cathode area, sq cm	Pressing pressure, N/sq m	Oxide coating	Activator percent carbon	Test time, hr	Cathode type	Cause of stopping
	Type and number	Size, cm	Type	Size, cm	Before pressing	After pressing	Before pressing	After pressing							
1	Four tantalum	0.051	Tungsten	0.013	1.00	0.95	10.00	8.90	28.0	48×10^{-7}	Barium carbonate	5.7	4870	Long brush	Grid short-circuited at 4858 hr
2	Four tantalum	.051	Tungsten tantalum (3:1)	.008	1.50	1.45	5.72	4.92	25.7	34	Barium carbonate	---	1809	Brush	Cathode open
3	Tantalum	-----	Tantalum	.008	1.00	.86	3.81	3.75	10.9	48	Radio Mix 3	---	2060	Indirectly heated	Cathode open
4	Four tungsten	.023	Tungsten	.008	1.50	1.35	5.72	5.07	24.3	34	Barium carbonate	5.7	840	Brush	Vaporizer open
5	------	-----	-----	-----	----	----	----	----	11.3	34		7.8	4179	Oxide magazine	To examine cathode
6	------	-----	-----	-----	----	----	----	----	11.3	34			3240	Oxide magazine	To examine cathode
7	Four tungsten	0.023	Tungsten	.008	1.50	1.11	5.72	5.07	19.6	3			1150	Brush	High power
8	Four tungsten	.051	Tungsten	.008	1.27	.95	4.13	3.81	12.8	3			1361 1041	Four brushes (cathode changer)	Grid short-circuited at 158 hr; to change cathodes
9	Four tungsten	-----	Iridium	-----	1.43	----	7.30	----	32.8	-------	Radio Mix 3	---	1360	Indirectly heated	Grid short-circuited at 1272 hr; high power

TABLE II. - ELECTRON-BOMBARDMENT THRUSTOR OPERATING

CONDITIONS FOR DURATION TESTS

[Anode voltage, V_I, 3000 V; accelerator voltage, V_A, -2000 V.]

Thrus-tor	Discharge potential, V	Beam current, A	Accel-erator current, mA	Nominal cathode power, W/sq cm	Emission current, A	Nominal emission current, A/sq cm	Magnetic field, T	Neutral flow equiva-lent, A	High-voltage breakdowns
1	20 to 27	0.250	2.5 to 4.5	7.1	4 to 8	0.21	10.4 to 12.8×10[4]	0.35 to 0.34	1188
2	20 to 40		2.6 to 6.0	7.8	3.5 to 8	.22	10.8 to 12.0	.29 to .39	1933
3	18 to 30		2.0 to 4.5	9.2	3 to 7	.42	8.8 to 13.6	.31 to .48	995
4	22 to 38		2.5 to 5.0	8.8	4.5 to 6	.22	9.6 to 10.4	.30 to .38	703
5	20 to 22		2.0 to 3.0	11.0	5 to 7	.53	11.9 to 12.2	.33 to .41	677
6	25		2.5 to 4.0	15.5	4 to 6	.44	12.4 to 12.9	.29 to .88	751
7	27 to 40		4.0 to 10.0	12.7	4 to 10	.36	[a]2.0	.36 to .75	1632
8	35 to 40		-----	19.5	4 to 6.5	.41	10.0 to 12.6	.53 to .57	----
9	18 to 35		4.0 to 12.0	12.2	3 to 8	.17	15.0	.56 to .68	2121

[a]Permanent magnets used.

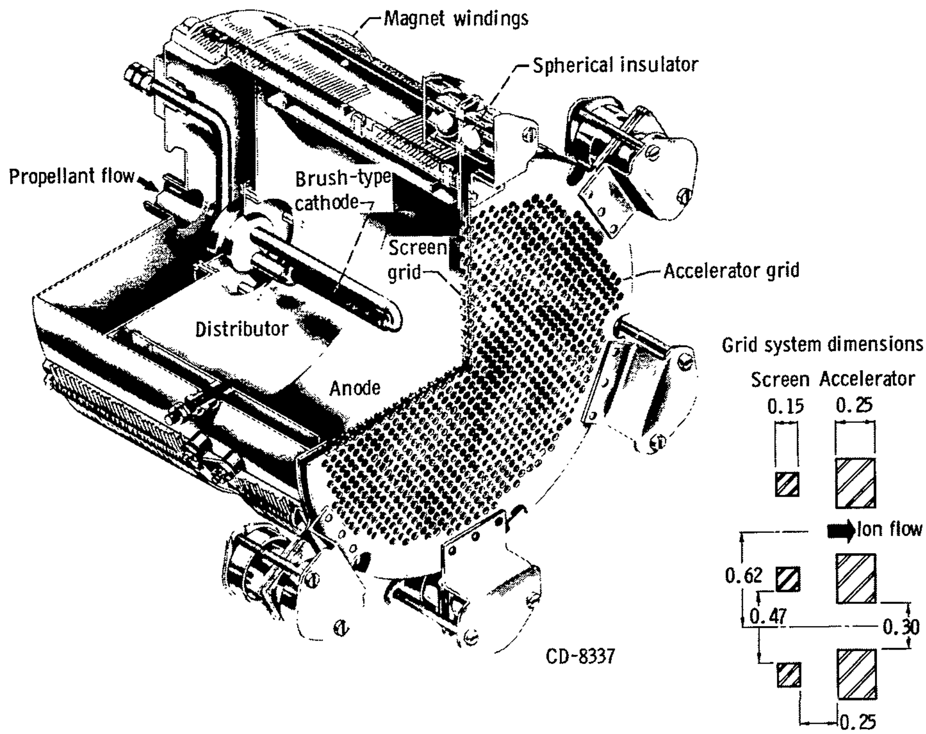


Figure 1. - 20-Centimeter-diameter electron-bombardment ion thrustor. (All dimensions are in centimeters.)

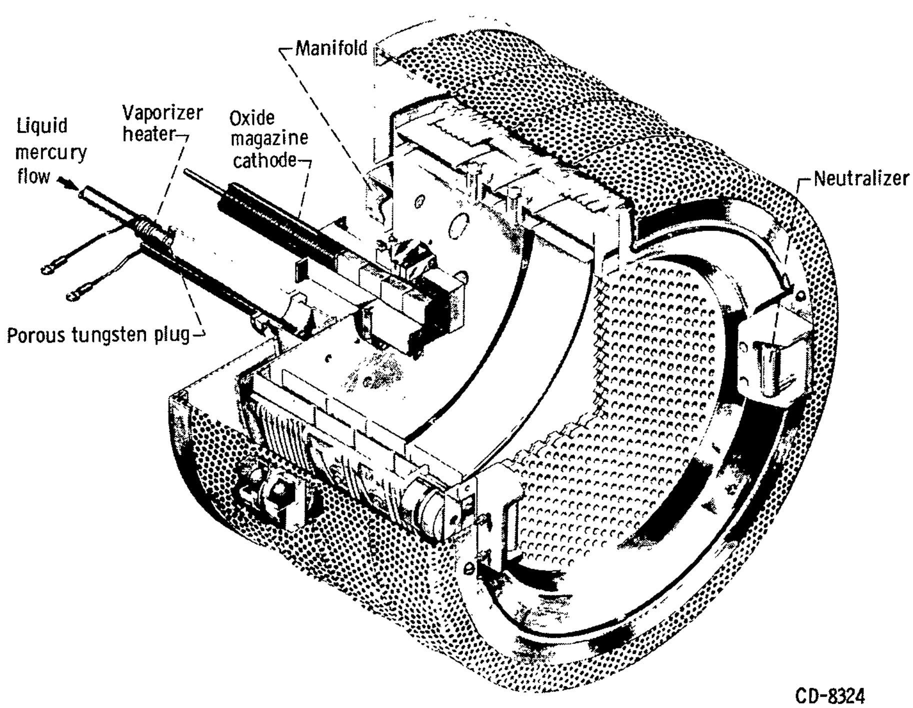


Figure 2. - 15-Centimeterldiameter electron-bombardment ion thrustor.

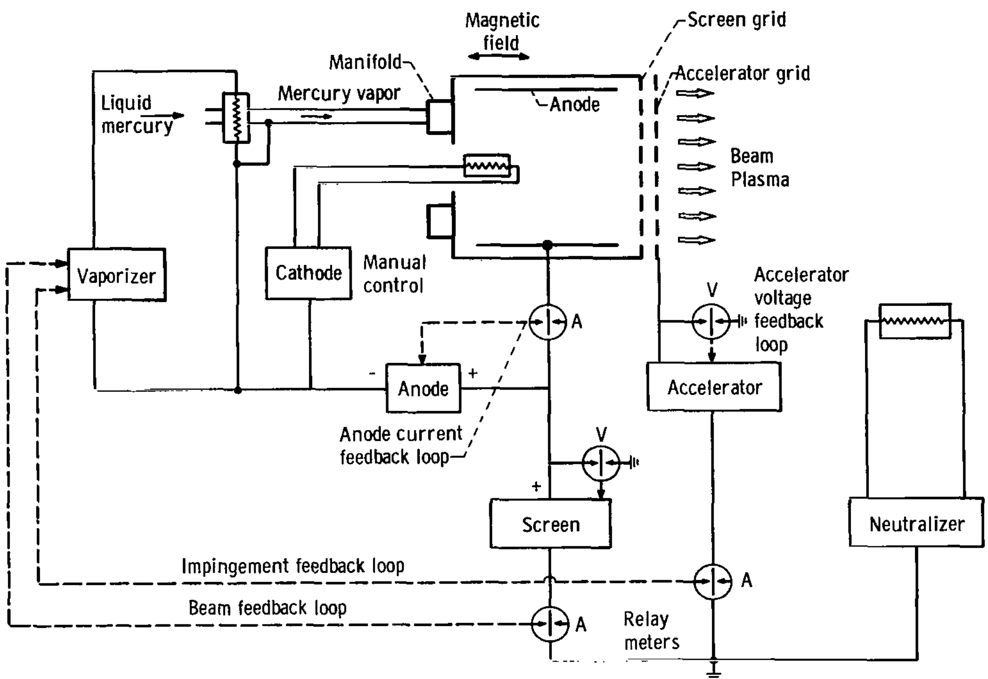


Figure 3. - Schematic diagram of electron-bombardment thrustor power supplies and control system.

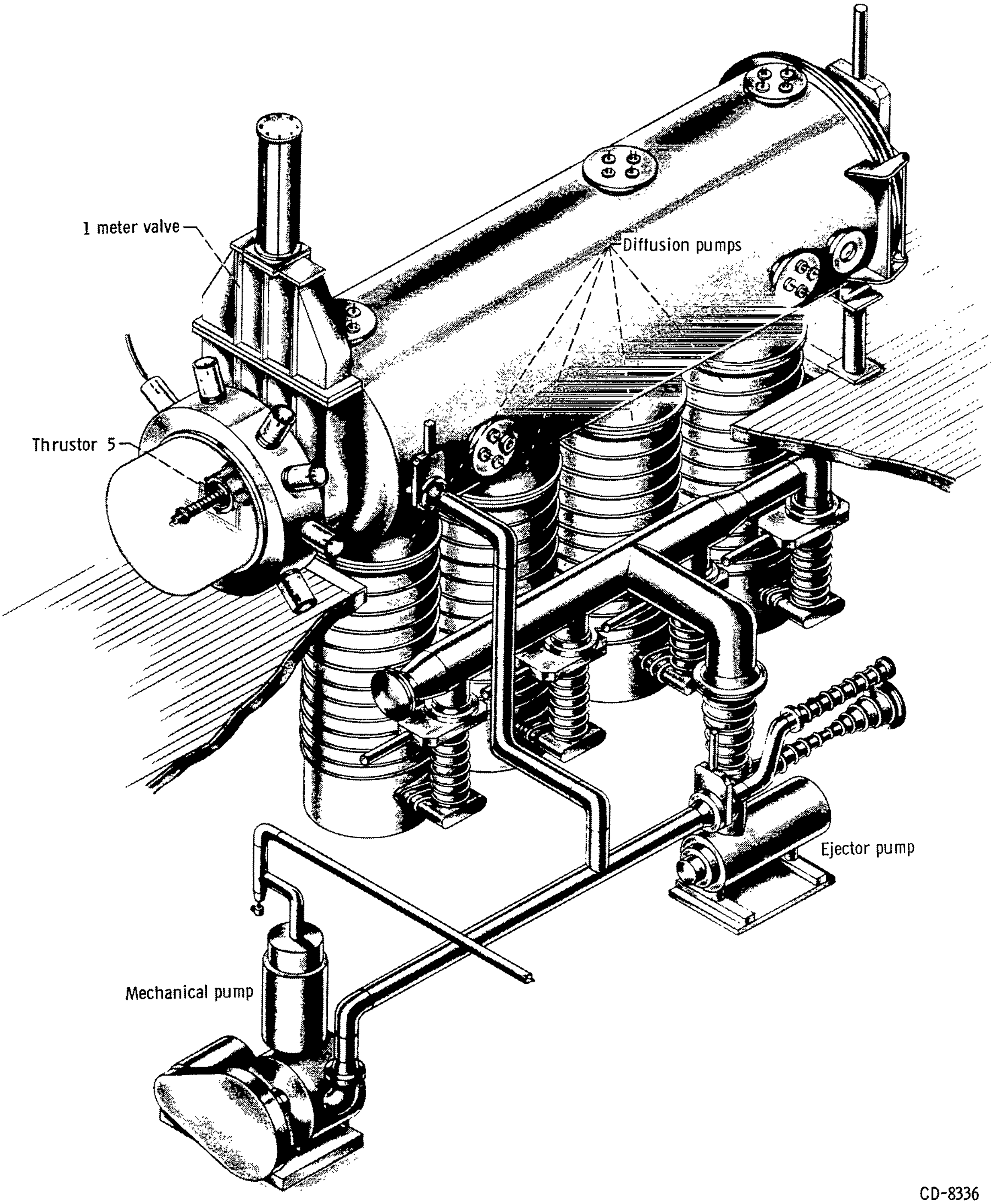


Figure 4. - Thrustor installed in 1.5- by 5-meter vacuum-tank facility.

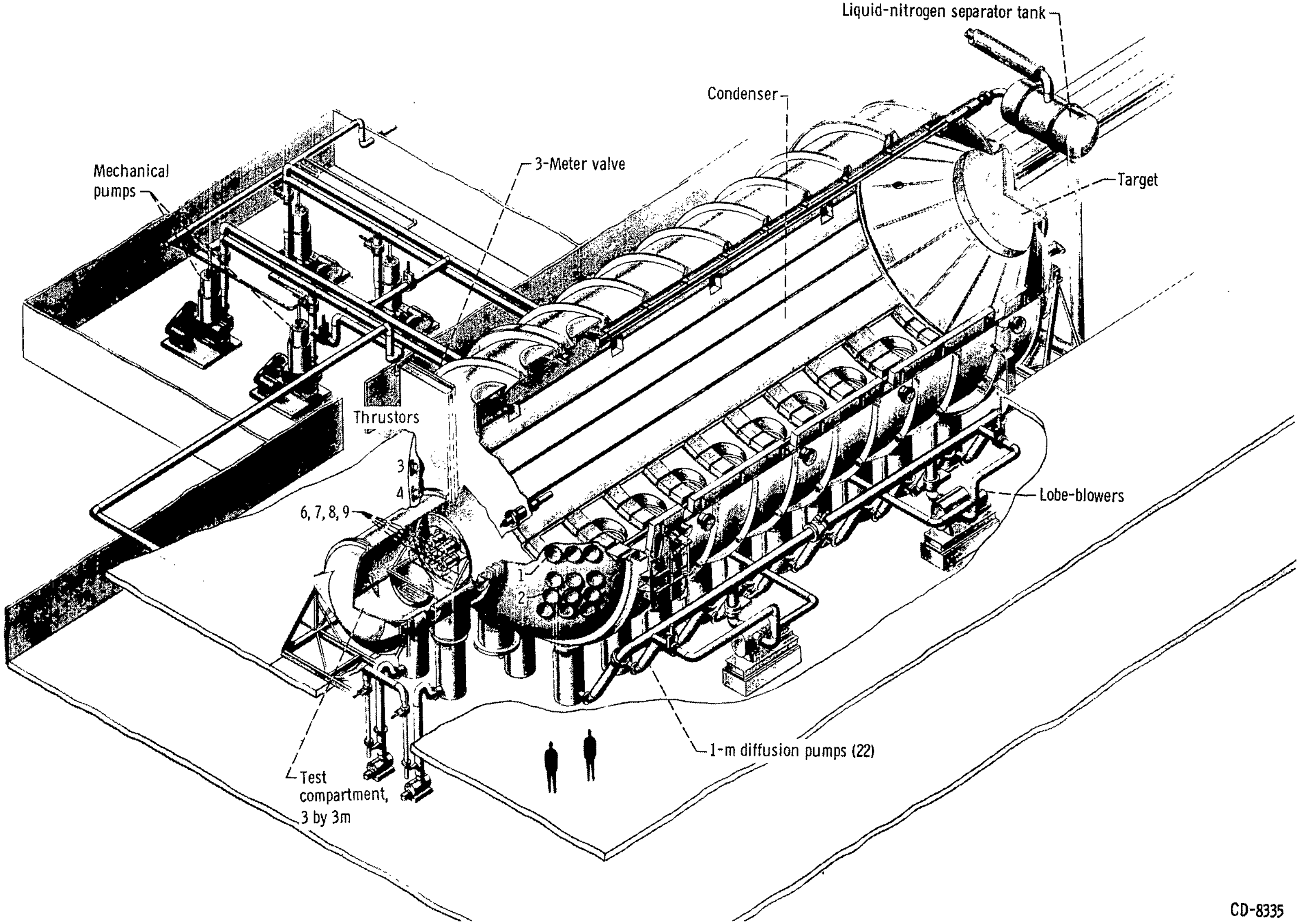


Figure 5. - Eight-thrustor stations in 7.5- by 21-meter vacuum-tank facility.

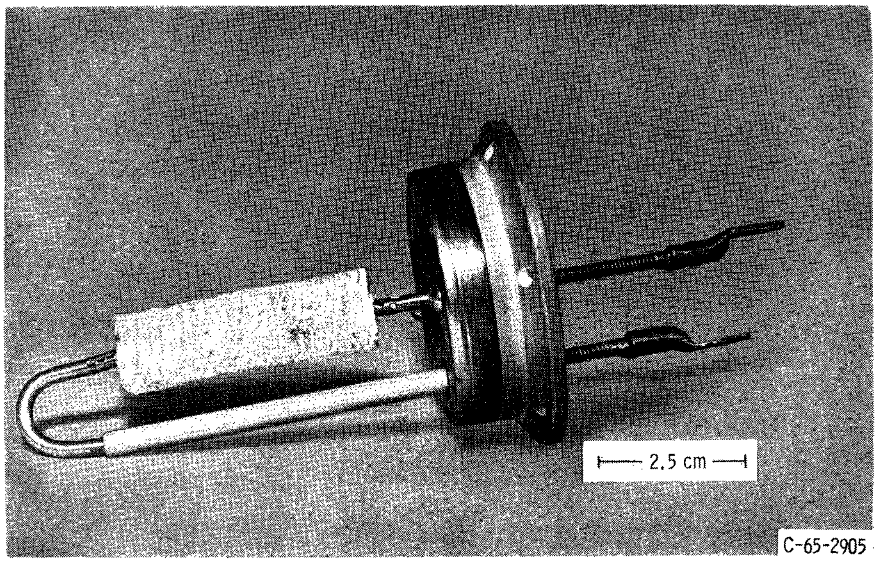


Figure 6. - Brush-type cathode used in thrustor 2.

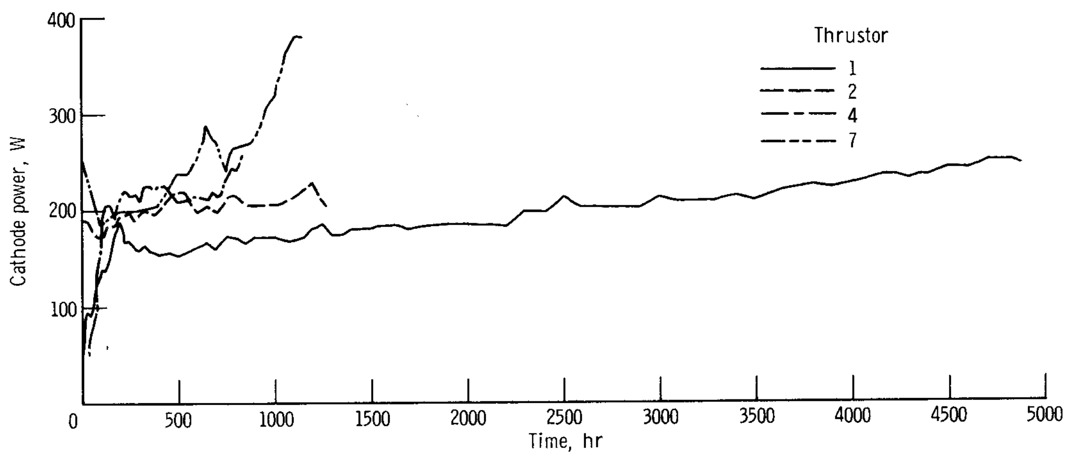
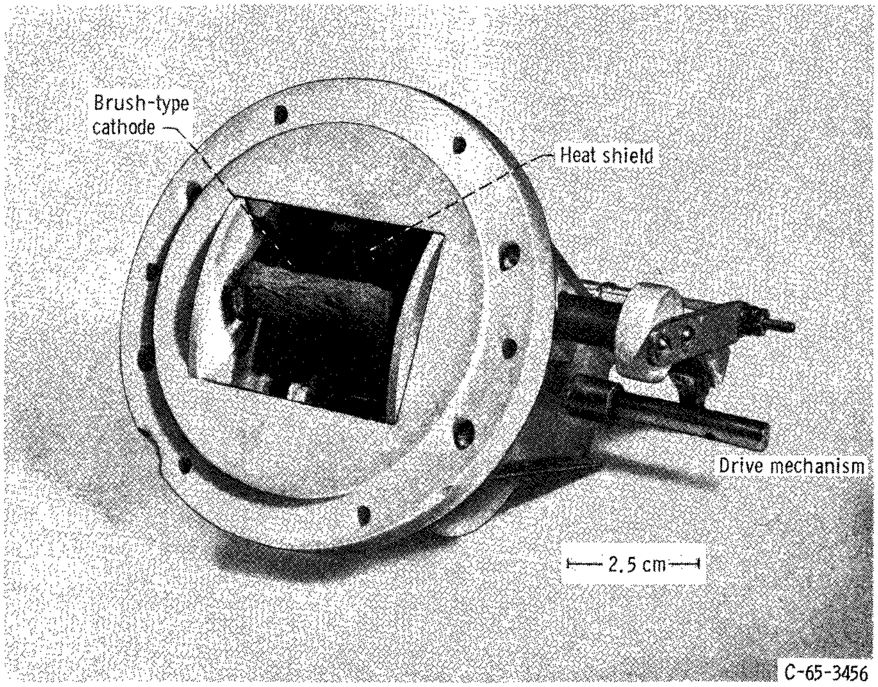
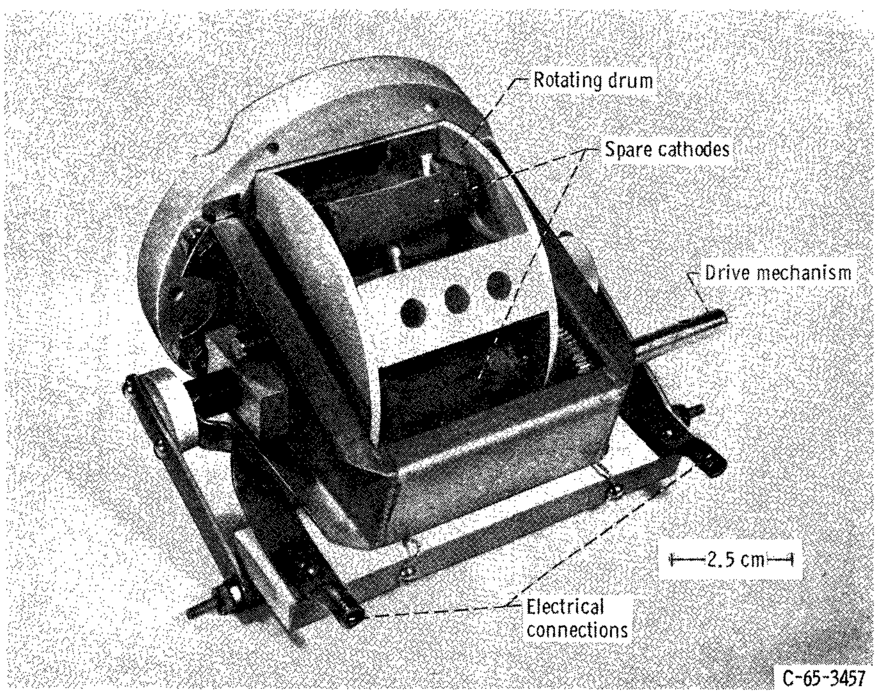


Figure 7. - Cathode power as function of time for oxide-coated brush cathodes in operating thrustors. Beam current, 0.25 ampere; anode voltage, 3000 volts.



(a) Cathode in operating position.



(b) Spare cathodes, electrical connection, and drive mechanism.

Figure 8. - Cathode changer used in thrustor 7.

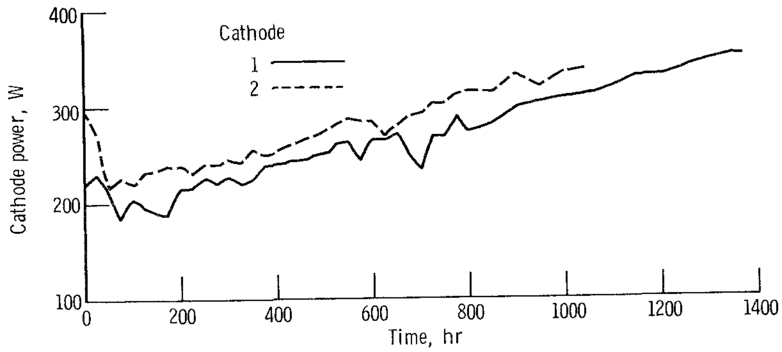


Figure 9. - Cathode power as function of time for oxide-coated brush cathode mounted in cathode changer.

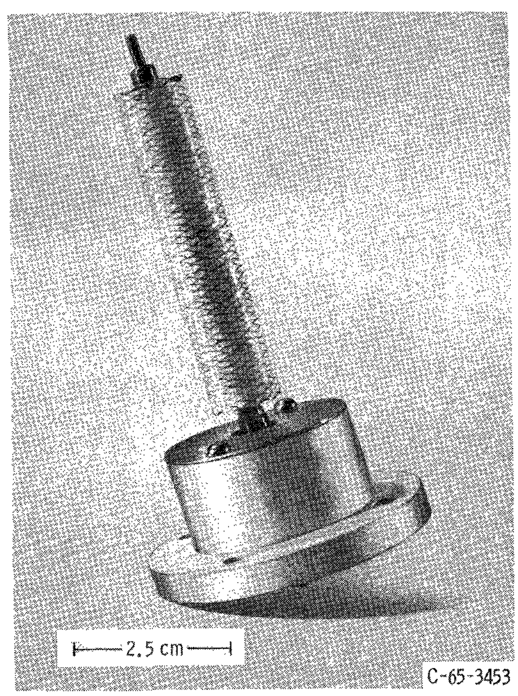


Figure 10. - Indirectly heated cathode used in thrustor 9.

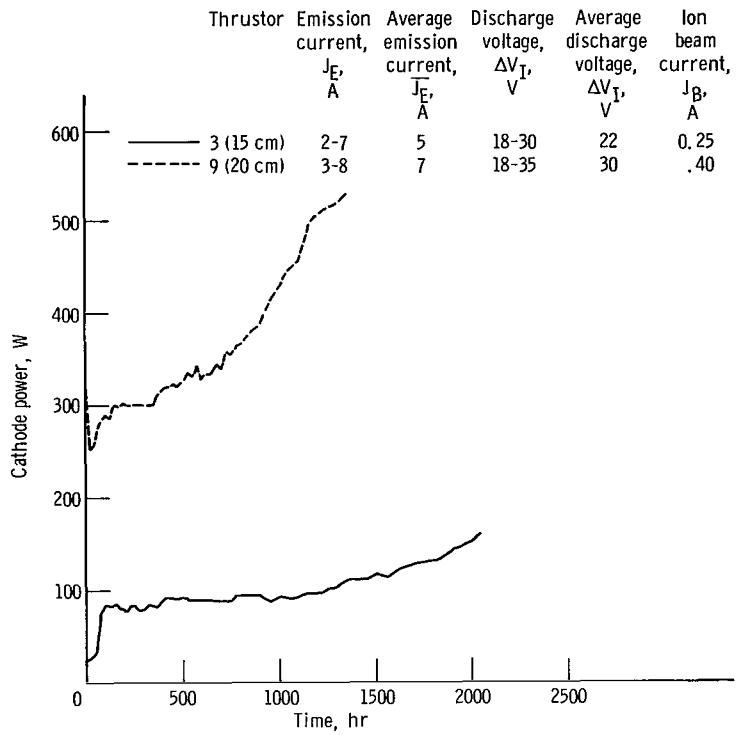


Figure 11. - Cathode power as function of time for indirectly heated cathode in operating thrustors. Anode voltage, 3000 volts.

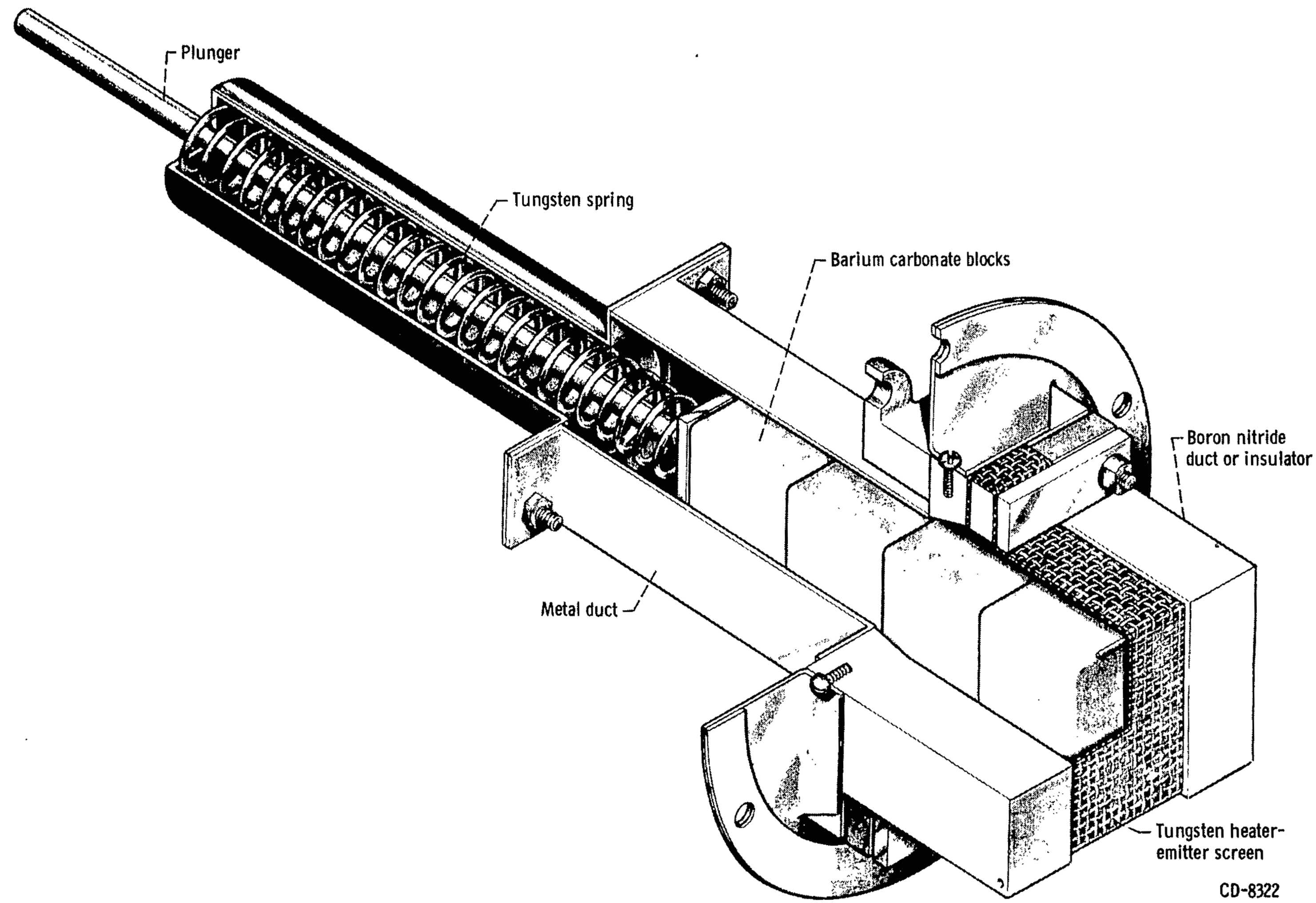
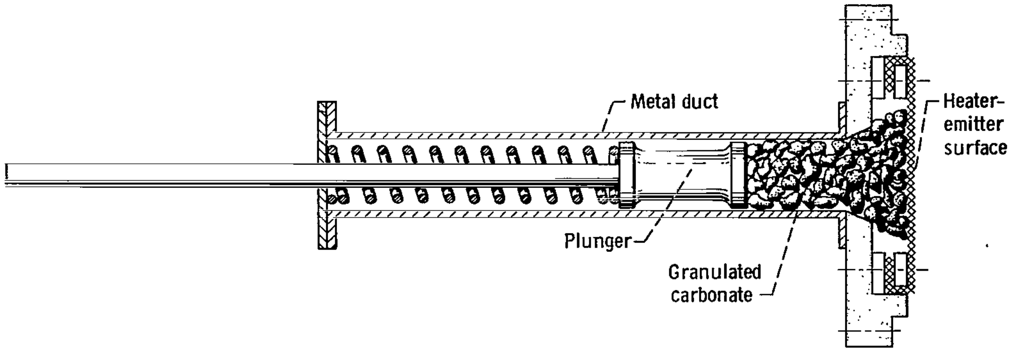
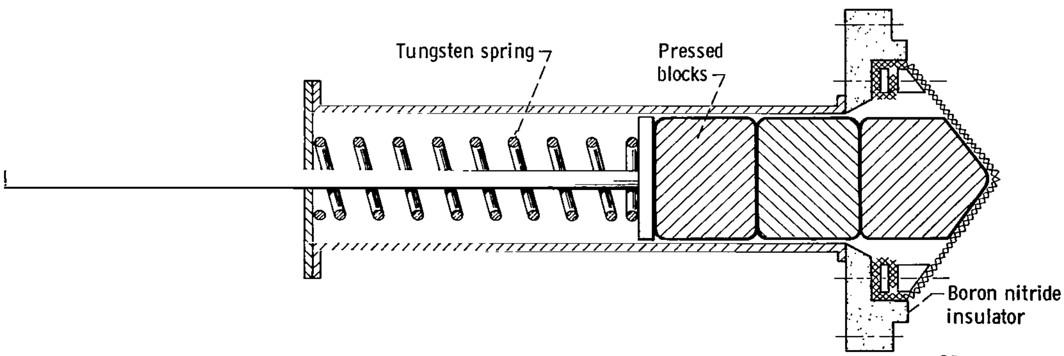


Figure 12. - Oxide-magazine cathode used in thrustors 5 and 6.



(a) Initial design.



(b) First modification.

Figure 13. - Early oxide-magazine configurations.

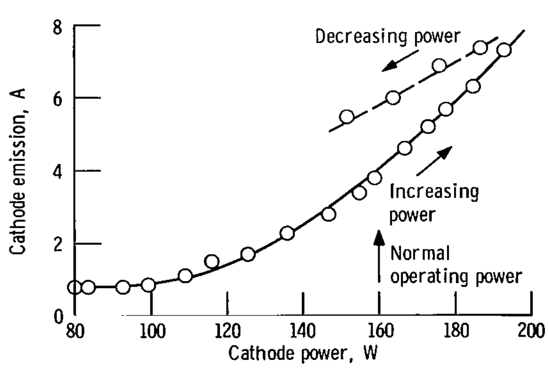


Figure 14. - Typical power-emission characteristics. Thrustor 6 oxide-magazine cathode after 925 hours of operation.

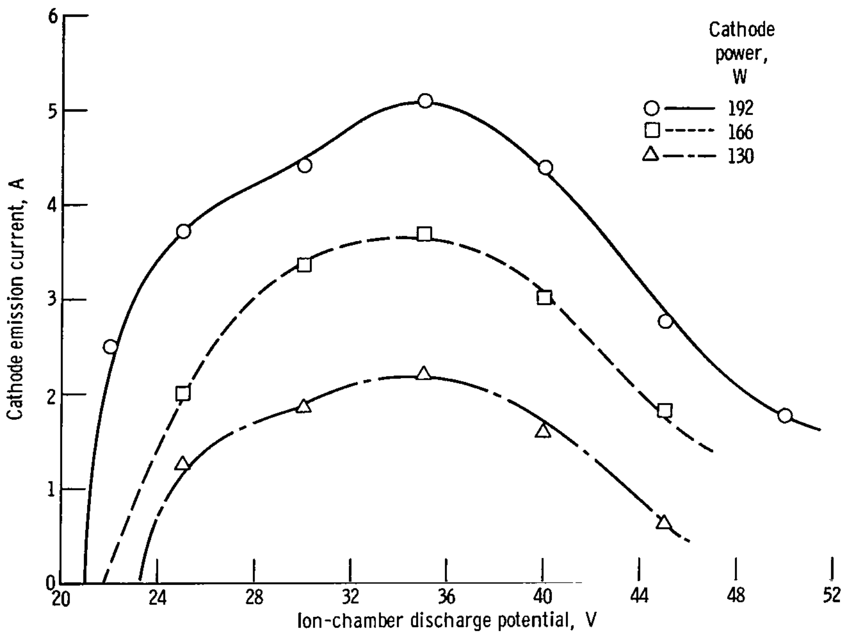


Figure 15. - Typical emission-ion-chamber discharge potential characteristics of oxide-magazine cathode for several values of cathode heater power.

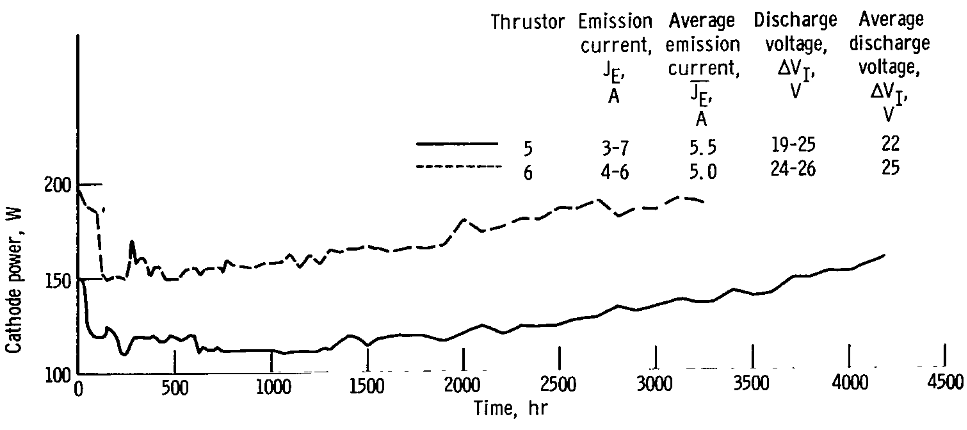


Figure 16. - Cathode power as function of time for oxide-magazine cathodes in operating thrustors. Beam current, 0.25 ampere; anode voltage, 3000 volts.

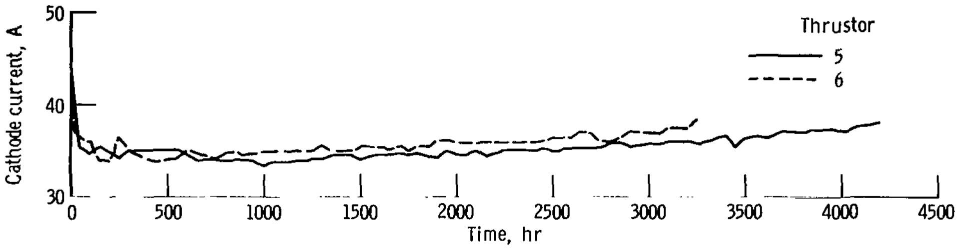
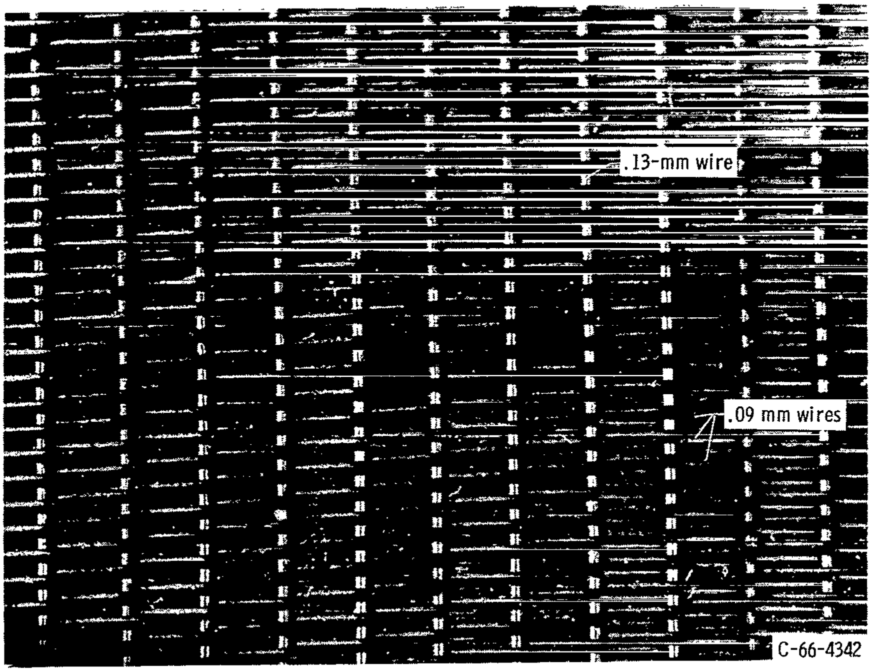
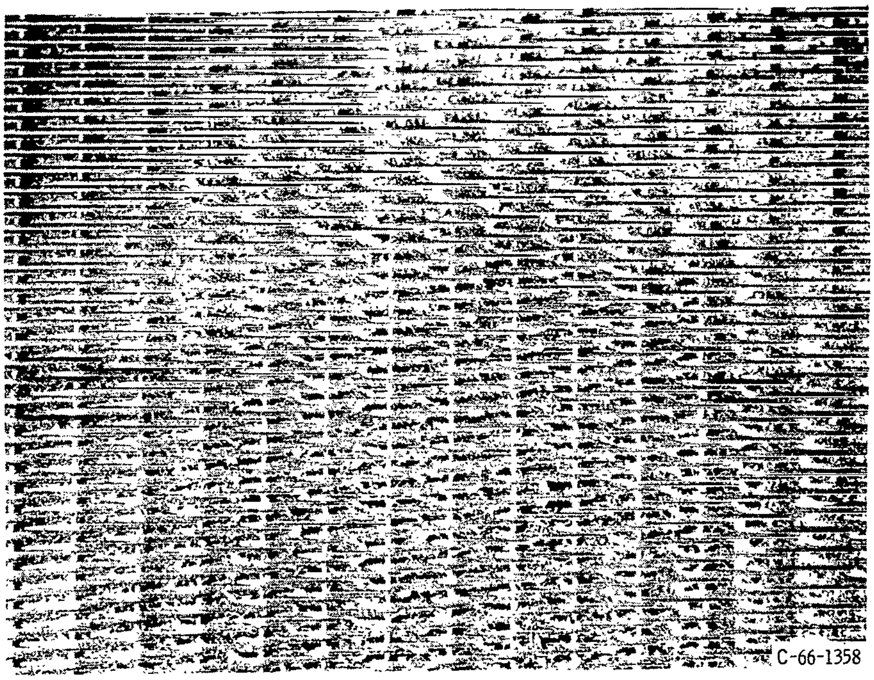


Figure 17. - Cathode current as function of time for oxide-magazine cathodes in operating thrustors. Beam current, 0.25 ampere; anode voltage, 3000 volts.



(a) Original screen.



(b) After 3240 hours of operation.

Figure 18. - Tungsten heater-emitter screen from cathode of thrustor 6.

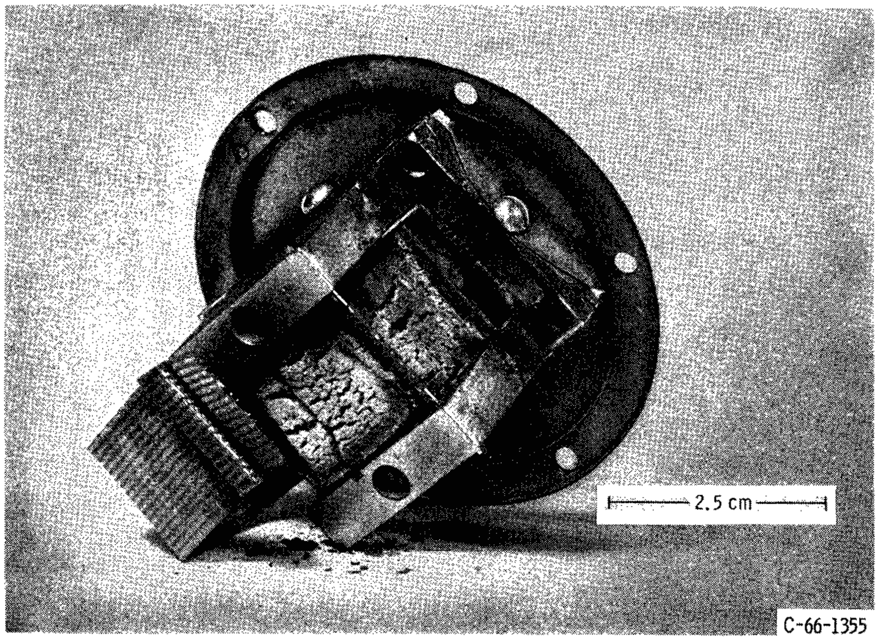
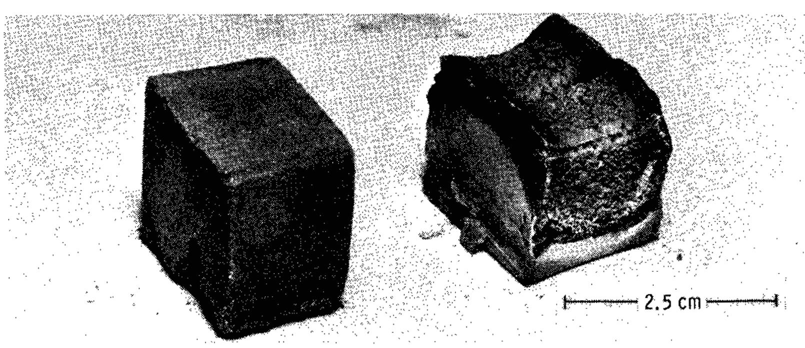


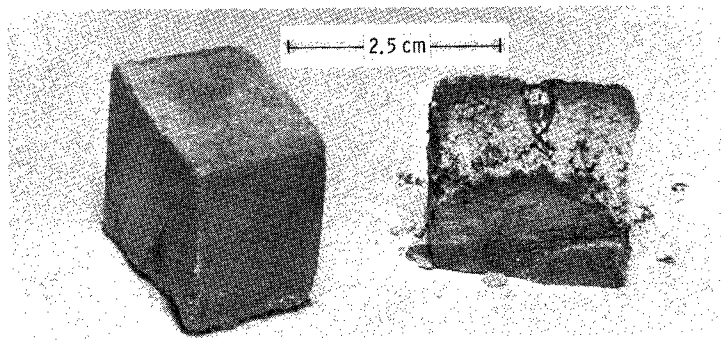
Figure 19. - Thrustor 6 cathode with heater-emitter screen swung aside to expose oxide blocks after 3240 hours of operation.



Block from metal duct　　Block contacting emitting surface

C-66-1854

Figure 20. - Oxide blocks from cathode of thrustor 5 after 4179 hours of operation.



Block from metal duct Block contacting emitting surface

C-66-1853

Figure 21. - Oxide blocks from thrustor 5 after 4179 hours of operation. Block contacting emitting surface cut in half to reveal depth of activator depletion.

NASA-Langley, 1967 —— 28 E-3725

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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